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PROVISIONAL APPLICATION FOR PATENT COVER SHEET

This is a request for filing a PROVISIONAL APPLICATION FOR PATENT under 37 CFR 1.53(c).

INVENTOR(S)

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☐ *Additional inventors are being named on the ___ separately numbered sheets attached hereto*

TITLE OF THE INVENTION (280 characters max)

SUB-PICO TESLA MAGNETIC FIELD DETECTOR

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ENCLOSED APPLICATION PARTS *(check all that apply)*

☒ Specification *Number of Pages* 14 ☐ CD(s), Number

☒ Drawing(s) *Number of Sheets* 9 ☒ Other (specify) Itemized Postcard

☐ Application Data Sheet. See 37 CFR 1.76

METHOD OF PAYMENT OF FILING FEES FOR THIS PROVISIONAL APPLICATION FOR PATENT *(check one)*

☒ Applicant claims small entity status. See 37 CFR 1.27.

☐ A check or money order is enclosed to cover the filing fees

☒ The Commissioner is hereby authorized to charge filing fees or credit any overpayment to Deposit Account Number: 50-1290

☐ Payment by credit card. Form PTO-2038 is attached.

FILING FEE AMOUNT ($): $80.00

The invention was made by an agency of the United States Government or under a contract with an agency of the United States Government.

☒ No.

☐ Yes, the name of the U.S. Government agency and the Government contract number are: ______

Respectfully submitted,

SIGNATURE [signature] Date 2/26/02

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TELEPHONE 212-940-8800 Docket Number: CARDM 19.258

USE ONLY FOR FILING A PROVISIONAL APPLICATION FOR PATENT

Sub-Pico Tesla Magnetic Field Detectors

BACKGROUND OF THE INVENTION

Field of Invention

The present invention relates generally to the field of superconducting quantum interference devices (SQUIDs). More specifically, the present invention is related to magnetometers and magnetic gradiometer devices based on SQUIDs in an unshielded environment.

Discussion of Prior Art

SQUID magnetometers and gradiometers are the most sensitive magnetic field detectors that exist. Unfortunately, this unprecedented sensitivity comes at a price; they get overwhelmed by ambient noise and stop working when exposed to radio frequency interference (RFI). Thus, most often these devices can only be operated in heavily shielded enclosures. Therefore, it is beneficial to make such detectors operable in unshielded environment if they are to be successfully employed for practical applications. A major source of trouble is radio frequency interference (RFI). A SQUID's performance diminishes (loss of sensitivity) and in some cases where there is strong RFI, it can even cease to function. Sources of strong RFI include ultrasound machines in hospitals, AM and FM radio signals, or cellular communications transmissions.

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A simple but often impractical solution in prior art systems is to surround the system with a few layers of fine copper mesh and isolate the area of operation. The copper mesh cuts down RFI considerably, but doesn't eliminate it as it is impossible to cut down transmission through connecting cables. The SQUID itself is completely shielded inside a small niobium tube, but the gradiometer is the element that picks up the measurement signal and feeds it to the SQUID. Since the gradiometer cannot be shielded (otherwise it cannot pick up the signal to be measured), it couples the RFI into the SQUID. Thus, there is a need for a technique that allows the gradiometer to couple the signal of interest to the SQUID, without coupling the RFI.

The following references provide for a general description of interference in prior art SQUID systems, but they fail to provide for a filter circuit for shielding the SQUID from radio frequency interference.

The Japanese patent to Fujimaki (JP 4212079) provides for a SQUID magnetic field sensor, wherein damping resistors R1 and R2 are used to eliminate only the magnetic part of the RFI.

The non-patent literature to Ishikawa et al. entitled, "Effect of RF Interference on Characteristics of a DC SQUID System", and Koch et al (Appl. Phys. Lett., vol 65, pp. 100-102) entitled, "Effects of radio frequency radiation on the dc SQUID," provide background information related to RFI interference in SQUID systems.

The non-patent literature to Bick et al. ("SQUID Gradiometry for Magnetocardiography Using Different Noise Cancellation Techniques"), and Tarasov et al. ("Optimization of Input Impedance and Mechanism of Noise Suppression in a DC SQUID RF Amplifier") illustrate, in general, the use of noise cancellation techniques with a SQUID device.

The U.S. patent to Simmonds (5,319,307) covers improving SQUID performance. References to a superconducting shielding layer are directed to shielding the SQUID chip from RFI, and it should be noted that in general all SQUIDs, even those used in shielded enclosures, are kept inside a superconducting Nb tube with gradiometers connected from the outside through a small hole in the Nb tube.

The U.S. patent to Colclough (5,532,592) covers electronics (flux-locked-loops) in multichannel systems. It should be noted that the reference to a brass enclosure is a routine procedure in electronics to shield against RFI; but this procedure is inadequate against RFI transmitted through a wire that goes through enclosures.

The U.S. patent to Seppä (6,066,948) discloses damping individual junctions of a SQUID. It should be noted that this is a common procedure and more information regarding this procedure can be found in the book by Weinstock entitled, "Applications of Superconductivity" (Kluwer publishers, Netherlands, 2000). It should further be noted that this procedure allows for the damping of internal oscillations of junctions that affect operation of the SQUIDs and does not reduce RFI coupled to the SQUID itself.

The U.S. patent to Steinbach et al. (6,169,397) describes a method for damping internal resonances of the SQUID. The damping helps shield the SQUID from magnetic part of the RFI and is similar to the Japanese patent by Goto (JP 4160380) that provides for a general background in noise suppression techniques as implemented in prior art SQUID systems. Furthermore, the Japanese patent to Kawai (JP 7198815) appears to teach along the same lines as that of the Steinbach et al. patent.

SUMMARY OF THE INVENTION

Radio Frequency Interference (RFI) can get coupled in two different ways: electrically and magnetically. The present invention provides for a system and method for shielding a SQUID from such RFI without compromising the signal to noise ratio of the system. In the preferred embodiment, filter circuits are used to shield a SQUID from RFI, which enable the operation of SQUID based systems outside the shielded enclosures. The filter circuits are formed using a combination of resistors and capacitors, wherein the resistors shunt RFI magnetic flux from the input coil (and thus the SQUID) and the capacitor shunts electrical part from the SQUID itself by grounding out the RF voltage. It should be noted that even though a specific resistive and capacitive filter is used to illustrate the main idea, any other form of filter circuit that has similar properties (cut-off frequency and sharpness of characteristics) can be used. For example, one embodiment includes a superconducting filter made up of superconducting striplines that cuts out all components of RFI from getting coupled into the shielded SQUID from unshielded gradiometers.

The present invention allows for widespread usage of SQUID systems in unshielded environments, even in the presence of strong RFI. This opens up the possibility of employing SQUIDs in various biomedical and nondestructive evaluation applications without sacrificing performance.

BRIEF DESCRIPTION OF THE DRAWINGS

Figure 1 illustrates a schematic of the symmetric SQUID bias electronics, wherein the twisted (twisting is not shown) wire pairs prevent flux from threading the loop.

Figure 2 illustrates a schematic of the symmetric SQUID heater electronics, wherein the tightly twisted wire pairs (twisting is not shown) prevent flux threading the loop.

Figure 3 illustrates a schematic of a feedback/modulation coil as coupled to a SQUID.

Figure 4 illustrates a first embodiment of the present invention.

Figure 5 illustrates a second embodiment of the present invention.

Figure 6 illustrates an equivalent circuit diagram of the input coil for low frequency instances.

Figure 7 illustrates an equivalent distributed LC network circuit diagram of the input coil circuit for the high frequency cases.

Figure 8 illustrates a third embodiment of the present invention.

Figure 9 illustrates a fourth embodiment of the present invention.

Figure 10 illustrates a full schematic of the complete SQUID electronics operating in conjunction with the first embodiment of the present invention.

DESCRIPTION OF THE PREFERRED EMBODIMENTS

While this invention is illustrated and described in a preferred embodiment, the invention may be produced in many different configurations, forms and materials. There is depicted in the drawings, and will herein be described in detail, a preferred embodiment of the invention, with the understanding that the present disclosure is to be considered as an exemplification of the principles of the invention and the associated functional specifications for its construction and is not intended to limit the invention to the embodiment illustrated. Those skilled in the art will envision many other possible variations within the scope of the present invention.

RFI gets coupled into the SQUID in two ways, electrically and magnetically. RFI gets coupled into the SQUID by all the connecting wires acting like electrical antennae. It can also be coupled into the SQUID by magnetic flux threading the various loops formed by the wires connecting to the SQUID (especially the input and feedback coil circuits). Also, under certain circumstances, RFI produces a large DC field on the SQUID. The circuit analyses indicate that the present invention successfully cuts down RFI coupled either electrically or magnetically. Since the SQUID is a very low impedance device, it is affected more by the magnetic pick up, but the electrical pick up could also prove substantial, especially near and above the FM radio bands where all the connecting wires become transmission lines.

RFI and EMI get coupled into the SQUID through all the electronic connections. This is eliminated by the symmetric electronics that allows one to remove ground connection to SQUID. The symmetry of the electronics cut down the transmitted RF energy coupled into the SQUID.

The RFI picked up through the gradiometer, including the residual energy that is coupled through the feedback/modulation coil and rest of the electrical connections to the SQUID is eliminated using special symmetric filter circuits.

Symmetric SQUID electronics are used in the circuitry of the present invention as it eliminates ground loop issues. Furthermore, the symmetric electronics also cuts down most of the electrical RFI. This is illustrated in Figures 1 and 2, using SQUID bias and heater electronics as examples. The symmetry ensures that if the wires act as antennae, the RFI voltage induced on them cancels out at the location of the SQUID. The circuitry of the present invention further includes a simple RC filter ($f_c \sim$ 1-10 MHz) that prevents standing waves from being set up at resonant frequencies of the wire transmission line (~10-100s of MHz), the SQUID washer and the input, or the feedback/modulation coil resonator (~ a few GHz). Additionally, tightly twisted wire pairs (of the symmetric lines) ensure that no magnetic flux threads the circuit loop.

Figure 3 illustrates a description of the feedback/modulation coils, wherein a common coil shares the feedback and modulation circuitry. Magnetic interference through the loop is eliminated by tightly twisted wire pairs (i.e., $\Phi = 0$). It should be noted that antenna-like pick up of RFI can still be coupled to the SQUID through the capacitive coupling between the feedback coil and the SQUID washer. In one embodiment, C_f is about 10 pF and the modulation signal has components up to 1 MHz. Thus, a RC filter is chosen such that it has the effective bandwidth greater than 10 MHz and C is large enough (compared to C_f) to short most of the RFI from the SQUID. Representative values are $R = 100\ \Omega$ and $C = 1$ nF.

Figure 4 illustrates the input circuit of the present invention. An RC filter, as in Figure 2, can be used to cut down the antenna-coupled RFI, but in this case, also present is some magnetic flux threading the loop. This requires a resistive shunt to short out the flux from the input coil. Thus, in an extended embodiment, the RC filters of Figure 2 are combined with a shunt resistor as shown in Figure 5.

In order to better understand how the present invention works, a typical example is provided with parameters suitable for the system. It should be noted that specific examples and parameters are provided for illustrative and descriptive purposes only, and therefore should not be used to limit the scope of the present invention. The impedance values at various frequencies are tabulated in Table 1. This is for the circuit in Figure 4. The values of various parameters are: C_i = 140 pF (measured), L_i = 300 nH (as specified by SQUID manufacturer), C_g = 10 nF, R_s = 1.5Ω.

f (MHz)	Z_{Ci}	Z_{Li}	2*R_s	Z_{Cg}	Z_{Cg}+ R_s	~ dZ_{Ci}	~ dZ_{Li}
1	113Ω	1.8	3	16	17.5		
5	22.6	9	3	3.2	4.7		
100	1.13	180	3	0.16	1.6	11.3	18
500	0.226	900	3	0.032	1.5	11.3	18

Table 1. Impedance calculations for embodiment in Figure 4.

Impedance values for the circuit in Figure 5 are given in Table 2. All values are the same, except R_s = 3 Ω, and R_g = 1.5 Ω. It can thus be seen that this circuit is exactly equivalent to that in Figure 3.

f (MHz)	Z_{Ci}	Z_{Li}	R_g	Z_{Cg}	$Z_{Cg}+R_g$	$\sim dZ_{Ci}$	$\sim dZ_{Li}$
1	113 Ω	1.8	3	16	17.5		
5	22.6	9	3	3.2	4.7		
100	1.13	180	3	0.16	1.6	11.3	18
500	0.226	900	3	0.032	1.5	11.3	18

Table 2. Impedance calculations for embodiment in Figure 5.

At low frequencies, Z_{Li} is low enough and the wavelength of the RFI is long enough, that the equivalent input coil/SQUID washer circuit looks like Figure 6. It is clear from Tables 1 and 2, and Figures 4 and 5 that the grounding tap capacitor C_g can effectively shunt out the electrical component of RFI pickup from the SQUID because Z_{Ci} is greater than $Z_{Cg}+R_s$ (or $Z_{Cg}+R_g$ for Table 2).

At higher frequencies, this becomes a distributed LC network as shown in Figure 7. A representative approximation for this case is tabulated in the last two columns of Tables 1 and 2. These numbers are estimated by arguing that once the partial inductive impedance of a certain length of the input coil (Z_{Li} α length) starts to become larger than the capacitive impedance between the input coil and the SQUID (Z_{Ci} α 1/length, because the width is fixed for both L_i and C_i) over the same length segment, then it can effectively be considered a distributed LC network. This occurs around values of 10-20 Ω for Z_{Li} and Z_{Ci}. These numbers are still larger than $Z_{Cg}+R_s$ (or $Z_{Cg}+R_g$ for Table 2) by a factor of ~ 10 and the shunting still works.

At frequencies in excess of 1 GHz, the input coil/SQUID washer system becomes a TM mode resonator coupled to a damped (with R_s or R_g) input loop circuit, thus still avoiding instability of operation.

The shunt resistors (R_s) effectively remove the RF magnetic flux threading the input loop from affecting the SQUID by shorting the input coil: Z_{Li} is much greater than R_s for frequencies higher than 5 MHz (Tables 1 and 2). For lower frequencies, it still helps by shunting part of the RF flux away from the SQUID. In principle, this effect is further improved by reducing the value of the R_s. Unfortunately, there is a trade-off between smaller R_s and the flux noise it adds into the SQUID (from Johnson current noise coupled through the input coil $\Rightarrow \langle i_n \rangle = \sqrt{4k_B T/R} \Rightarrow \langle \phi_n \rangle = M_{in} \langle i_n \rangle$). Therefore, it is concluded that for the example system of the preferred embodiment, the optimum value is 3 Ω (2* R_s in Table 1 or R_s in Table 2). It should, however, be noted that the optimum value can be different based upon other parameters associated with the circuitry of the system of the present invention.

Also shown, are two other embodiments that address this issue by introducing a capacitor in series with the shunt resistor (Figures 8 and 9). The shunt capacitor C_s is chosen such that it forms a high pass circuit (with R_s and L_i) that blocks low frequency flux noise from getting to the SQUID.

The embodiment in Figure 4 is simple and compact and thus more resistant to parasitic effects. The embodiment in Figure 5 is a bit more complicated and thus presents us with issues of space and parasitic effects.

On the other hand, the embodiment in Figure 5 has the advantage that R_g can be made much smaller, thus making Z_{Cg}+R_g much smaller than Z_{Ci}. This will improve the RF voltage filtering. This does not, however, introduce additional flux noise into the SQUID because of symmetry of the circuit. Also, as shown in Figure 9, R_s can be lowered independently for filtering RF magnetic pickup, and only one additional capacitor, C_s needs to be added. In one embodiment, R_s is reduced, thus making Z_{Cg}+R_s much smaller than Z_{Ci}, for the RF voltage filtering to improve. But, now two additional shunt capacitors are needed, as shown in Figure 8. Additionally, Figure 10 illustrates a full schematic of the complete SQUID electronics with the embodiment shown in Figure 4.

Furthermore, even though a specific resistive and capacitive filter is used to illustrate the preferred embodiment, one skilled in the art can use any other form of filter circuit that has similar properties (cut-off frequency and sharpness of characteristics). For example, one embodiment includes a superconducting filter made up of superconducting striplines that cuts out all components of RFI from getting coupled into the shielded SQUID from unshielded gradiometers.

CONCLUSION

A system and method has been shown in the above embodiments for the effective implementation of a sub-pico tesla magnetic field detector. While various preferred embodiments have been shown and described, it will be understood that there is no intent to limit the invention by such disclosure, but rather, it is intended to cover all modifications and alternate constructions falling within the spirit and scope of the invention, as defined in the appended claims. For example, the present invention should not be limited by specific hardware or type of filter circuit. Thus, one skilled in the art can envision using other forms of filter circuits (e.g., a superconducting filter made up of superconducting striplines) having similar properties (cut-off frequency and sharpness of characteristics).

ABSTRACT OF THE DISCLOSURE

Filter circuits are used to shield a SQUID from radio frequency interference (RFI) without compromising the signal-to-noise ratio of the system. The filter circuits are formed using a combination of resistors and capacitors. The resistors shunt RFI magnetic flux from the input coil (and thus the SQUID), while the capacitor shunts electrical part from the SQUID itself by grounding out the RF voltage.

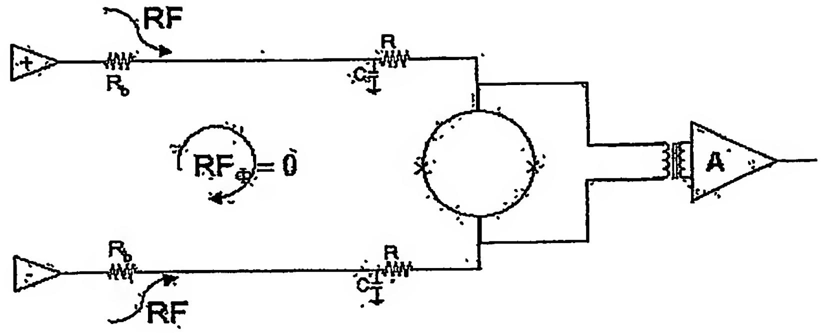

Figure 1

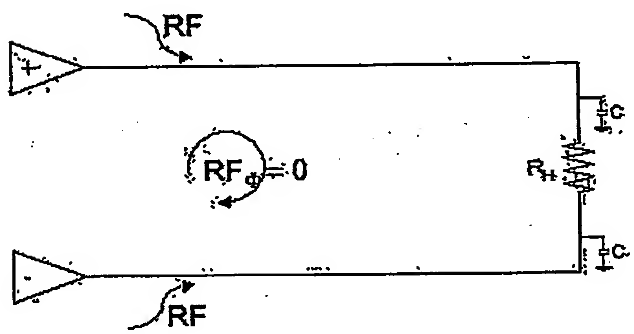

Figure 2

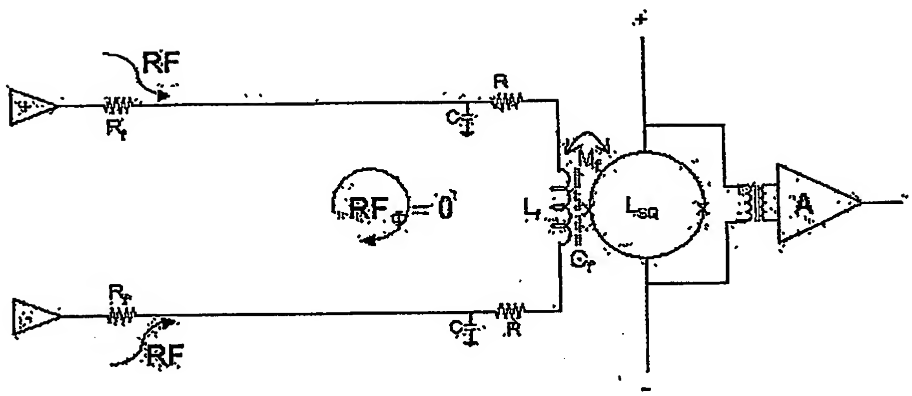

Figure 3

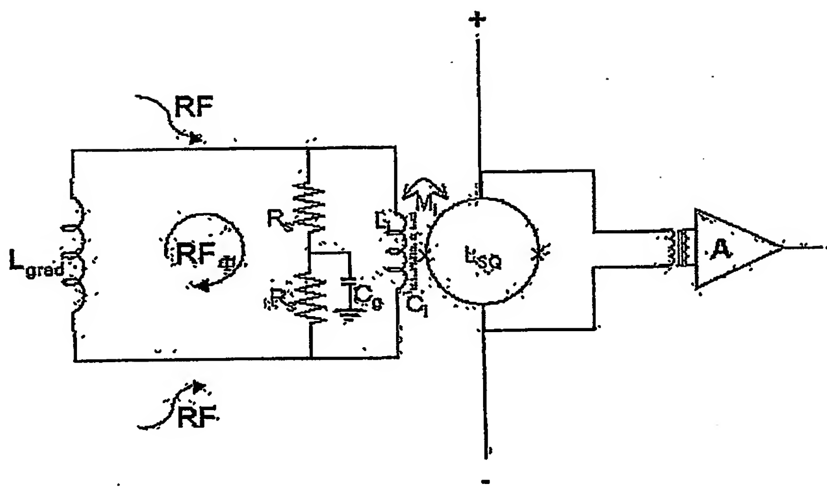

Figure 4

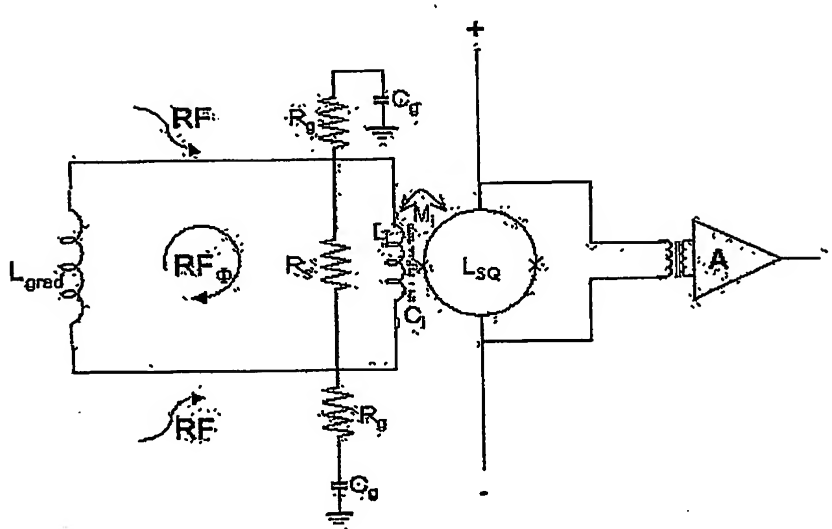

Figure 5

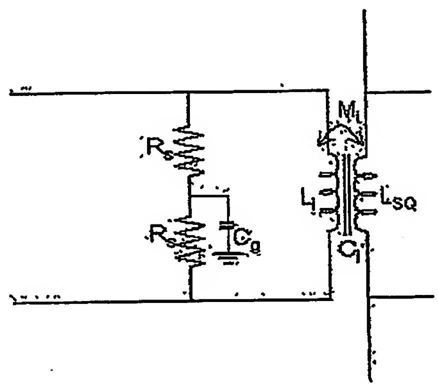

Figure 6

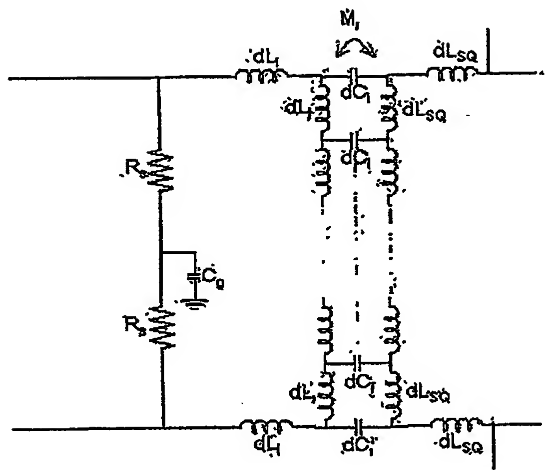

Figure 7

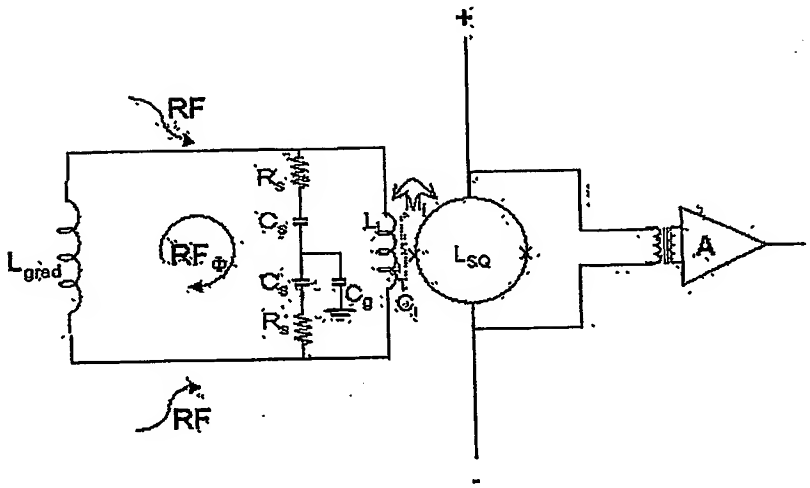

Figure 8

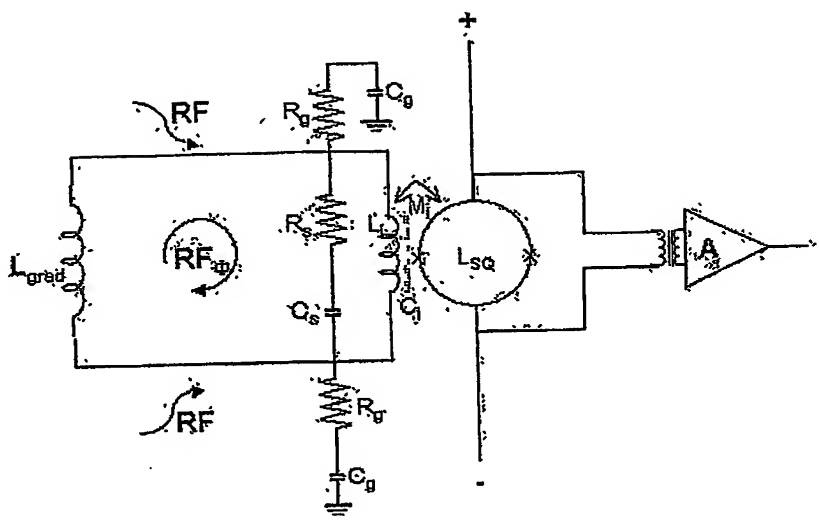

Figure 9

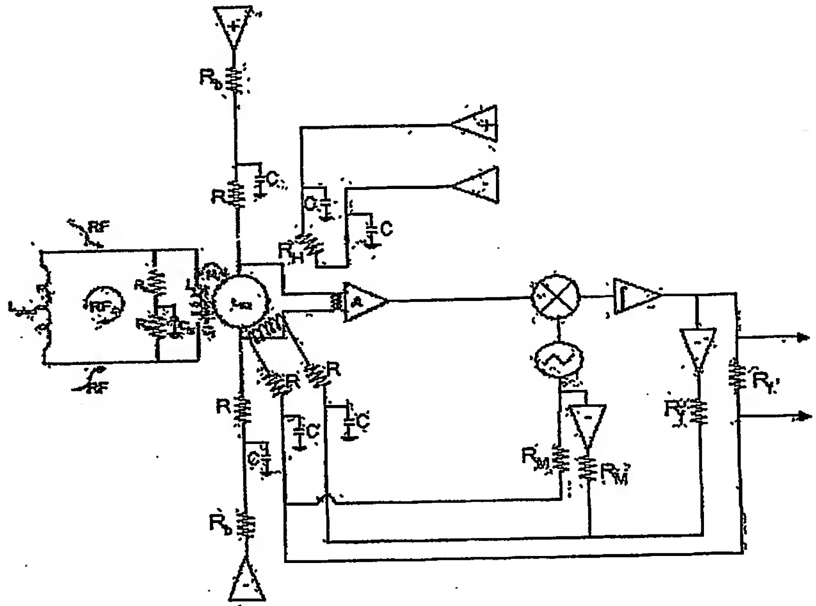

Figure 10